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DICHROIC FILTER SPECIFICATION FOR COLOR ADDITIVE DISPLAYS:

I. Preliminary Tolerance Determination and the C.I.E. Designations for Coding Colors

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AFLC, GAFB, N.Y., 31 Aug 66-134

FOREWORD

The effort described is a Rome Air Development Center in-house project. It is the last report in a series funded completely by Independent Research Funds (Discretionary Fund Item: DS-63-15). The author wishes to express his appreciation to the numerous members of the Display Techniques Branch who provided the technical support necessary to this investigation. Special thanks are directed to Dr. Raymond J. Christman for his pains-taking review of this report and his many helpful suggestions for improvement.

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ABSTRACT

Twelve pairs of dichroic filters were used in a xenon-source additive color projector to determine their effects upon observer use of the seven color codes customarily employed in Command-and-Control visual displays. The particular filters used were selected on the basis of previously published research. The resultant primary color codes and white were described in CIE terms for more ready comparison with color discrimination literature.

Results indicated that the blue filter should reflect energies well into the green region of the spectrum for adequate seven-color production. No over-all differences were found among the red dichroics, although red filters interacted significantly with coding colors. It was concluded that the relative efficiencies of the seven color codes may be tailored to anticipated or present operational need by the utilization of narrow filter tolerance. Broader tolerances around 516 nanometers for the blue filter cutoff and 585-590 nanometers for the red cutoff should result in an adequate set of seven coding colors. A comparison of several studies completed over the past two years seemed to suggest that over-all display brightness may have almost as significant an effect on observer performance as the selection of filters.

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SECTION I

INTRODUCTION

The Display Techniques Branch of Rome Air Development Center has undertaken a continuing effort in the area of color-coding. This task is aimed at developing specifications for color-producing devices for information displayed under a variety of conditions likely to be found in operational systems.

A first report on this problem was "Color Specification for Additive Color Group Displays" (Rizy, 1965), dealing with additive color techniques and xenon projection lamps. In that report, several preliminary goals were met:

- A survey of the literature dealing with the color discrimation area and the use of color in displays was presented.
- A sensitive experimental task and an adequate measure of performance were developed.
- Two optimum dichroic filter pairs for the production of seven coding colors were identified.
- General coding characteristics and problems of the various colors were described and analyzed.
- The interaction of filters and coding colors was examined. One of the two optimum filter pairs produced a statistically better white coding color than the other pair. No other significant differences between the two optimum pairs were identified.

Description of the obtained primaries was given in foot-lamberts, since at the time an adequate colorimetric device was not available. Although these measurements, combined with indices of the display environment, could provide some generalization to the operational case, relationships between colors obtained from a display projector and prior color research were unfortunately obscure.

PROBLEM

The first objective of the present investigation was to estimate the amount of tolerance around the cutoff points of the optimum filters identified in the previous study. Tolerance in the specification of dichroic filters may be defined in psychophysical terms as the limit of physical differences from the optimum filter curve that produces observer performance statistically equivalent to performance on the optimum filter.

The second aim was to relate obtained coding colors to the chromaticity diagram of the Commission Internationale de l'Eclairage, the CIE diagram. This step would permit analysis of the further relationship of observer performance on obtained colors to basic color discrimination work such as K. L. Kelly's breakdown of the CIE diagram into color names (1943) and Deane Judd's summary of research into areas of perceptible color differences (1950).

Kelly's findings, reproduced in summary in Figure 1, appeared to have prima facie value for color-coding information when those color codes should be recognized in absolute terms, as one of a finite series of coding categories, without the necessity of a comparative stimulus being shown simultaneously with the coded data. Ideally, the obtained red color code should fall in the red area of the diagram, the yellow in the yellow section, etc.

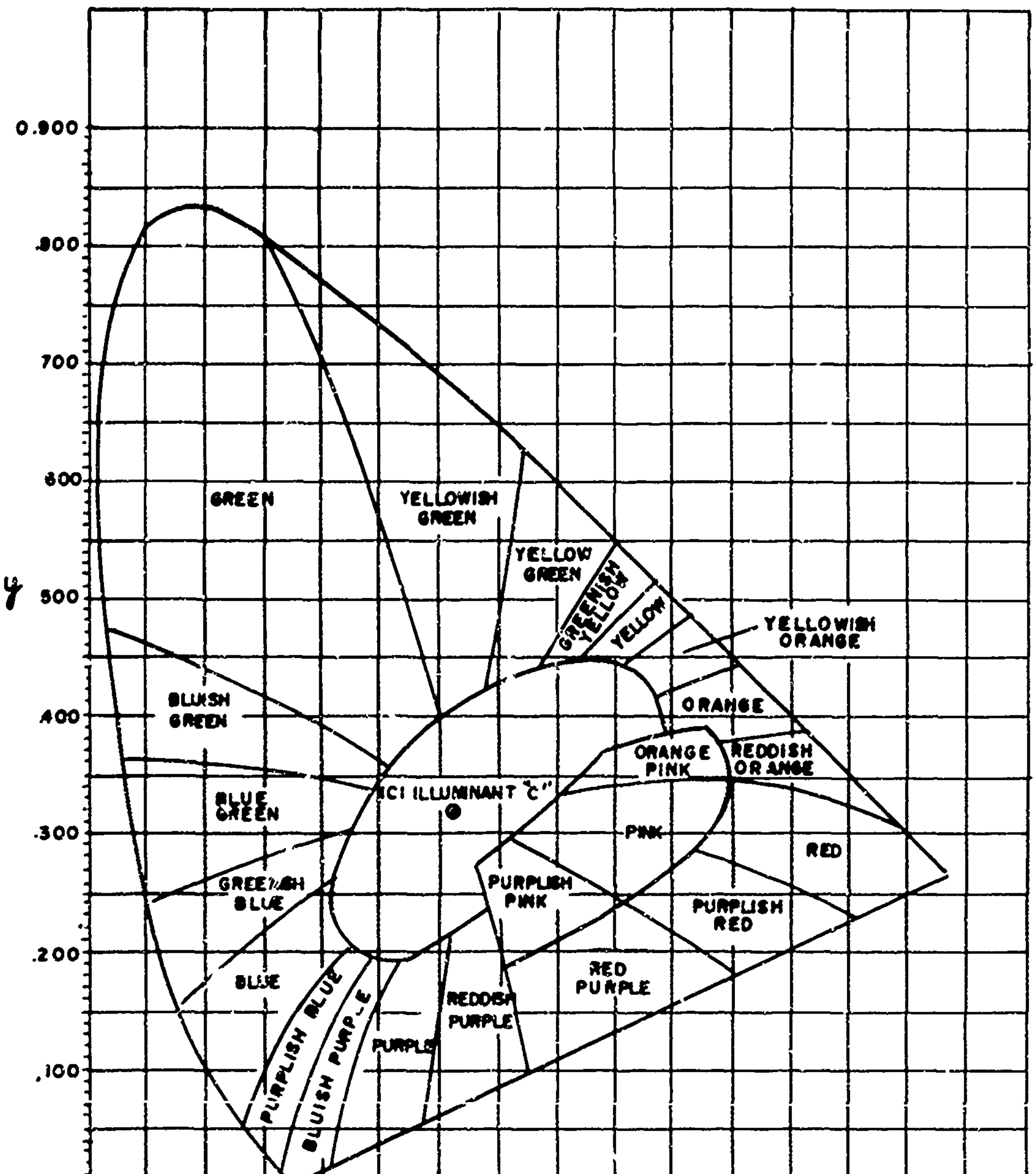

Figure 1. The CIE Diagram Delineated into Areas Corresponding to Color Names (After Kelly, 1943)

One problem encountered in the direct application of Kelly's findings was that the regions for three of the common codes, magenta, cyan and white, were not strictly defined. Another difficulty was that, speaking in practical terms of cost and existing display constraints, the mid-points of these areas, or any entire area itself, may not be achieved. The question would then be whether or not the obtained colors were sufficiently discriminable.

This latter difficulty was met in part by Judd's summary of findings in Figure 2. Whereas color names were not explicitly dealt with by Judd, his estimations of areas of confusability are useful in predicting color discrimination. Figure 2 is, however, an approximation of the maximum confusion area around a few selected points, none of which would probably coincide with color codes used in present experimental displays. Inferences drawn from Judd would have to involve interpolation between points on the diagram.

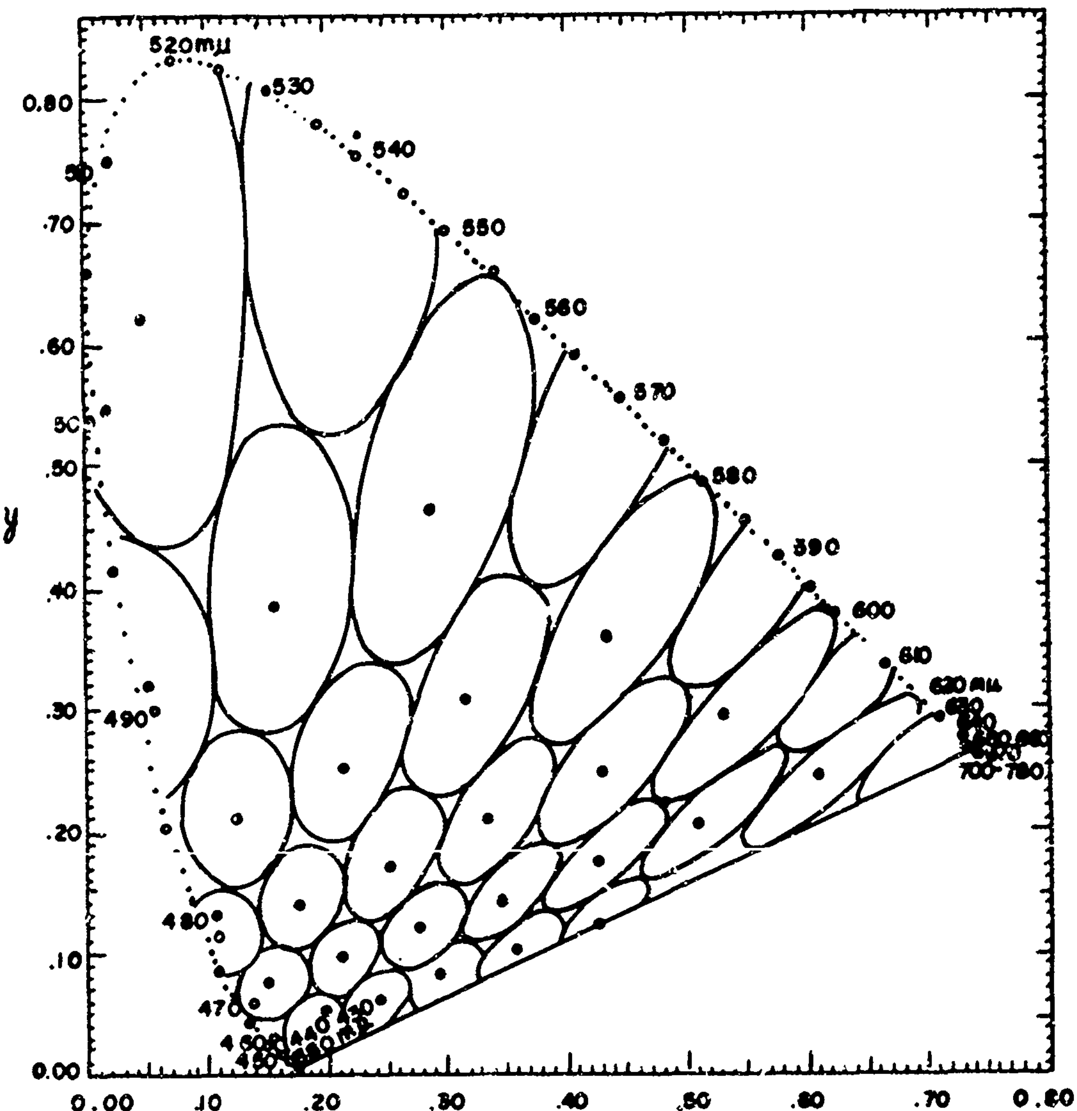

Figure 2. Approximate Perceptibility of Chromaticity Differences on the CIE Diagram (After Judd, 1950)

Figure 2 did suggest explanations for previous findings in this area. The direction of the major axes of the ellipses indicated the likelihood that green and cyan, yellow and white could be confused. The areas of the ellipses suggested that blue, red and magenta were not likely to be confused with other colors. This coincided with a finding of the previous study (Rizy, 1965).

If a relationship develops between the type of observer performance finding dealt with in the present research and Kelly's and Judd's reports, the specification of future color-coding systems may be extremely simplified. Proposed or obtained colors need only to be plotted and compared to the two standards. If Kelly's data indicate reasonable color fidelity and Judd's figure shows good color separation and highly probable discrimination, the colors can be assumed to be adequate. This rationale was recently adopted by the Electro-Optics Section of the Display Techniques Branch, when Kelly and Judd's data were applied to the specification of primaries for electroluminescent and laser displays.

SECTION II

APPARATUS AND PROCEDURE

1. APPARATUS

A Colorvision, Inc., 70 mm Additive Color projector with a 2.2 kw xenon source generated the display. Details on the operation and maintenance of the projector may be found in the instruction manual. The xenon source was powered by a Christie silicon rectifier, Model HX-2500-28. A white Lux-Matte front projection screen, six by eight feet, was placed 24 feet, 4 inches from the projection lenses. To compensate for the relatively short throw distance, the power to the source was reduced from a full operating load of 100 amps, 20-22 D.C. volts, to 50 amps, 16-18 volts, and the lamp was partially defocused.

A solenoid-operated shutter was installed in front of the projection lenses and activated by an Electra filtered D.C. power supply to control exposure time. Also part of the timing system were a Hunter timer, Model 111A, and a Standard electric clock. The experimenter initiated each trial by turning on the timer, energizing the solenoid and permitting the display to be projected on the screen. At the end of a 12-second exposure time preset into the Hunter timer, the timer circuit was broken and the shutter closed. The clock verified the length of the exposure.

2. VARIATION IN PRIMARY COLORS

The additive color projector is a three-channel projecting instrument with a single light source, using black and white transparency film with three separate fields. The white light is divided into blue, red and green components by two dichroic filters, which selectively reflect out two of the primaries. Each primary beam then passes through its own film field, through its own lens system, and onto the screen. The four remaining coding colors, yellow, magenta, cyan and white, are produced by the overlapping of primary images on the screen.

Experimental variation of the primaries and, consequently, of the entire seven-color code, was accomplished through the substitution of the blue and red dichroics within the projector optical assembly. The spectral reflectances of the dichroic filters are shown in Figure 3. The three blue filters reflected 50 per cent of the incident light at 506, 512 and 516 nanometers. The 516 filter was the optimum blue cutoff of the previous study. The red filters cut off at 581, 585, 590 and 595 nanometers. The 581 and 595 red filters were the optimum red filters mentioned previously.

A total of 12 filter combinations were obtained with the three blue and four red dichroics, in the normal order of blue filter/red filter (for a discussion of order, see Appendix). These pairs of filters produced somewhat different sets of coding colors.

3. CIE MEASUREMENTS OF CODING COLORS

The specification of obtained primaries in terms of the CIE coordinate system would facilitate explanation of differences between coding colors and between filters in terms of Kelly's and Judd's data. An Instrument Development Laboratories' Color-Rad abridged ratio-type colorimeter-spectroradiometer, model D-1, with current stabilized by two Sola constant voltage transformers in sequence, was used to obtain these measurements. Plots of the primaries and whites produced by the various filter combinations appear in Figure 4. Measurement was taken on the projector "open-gate," without film; and points on the figure represent the chromaticities of colors at the projection lenses.

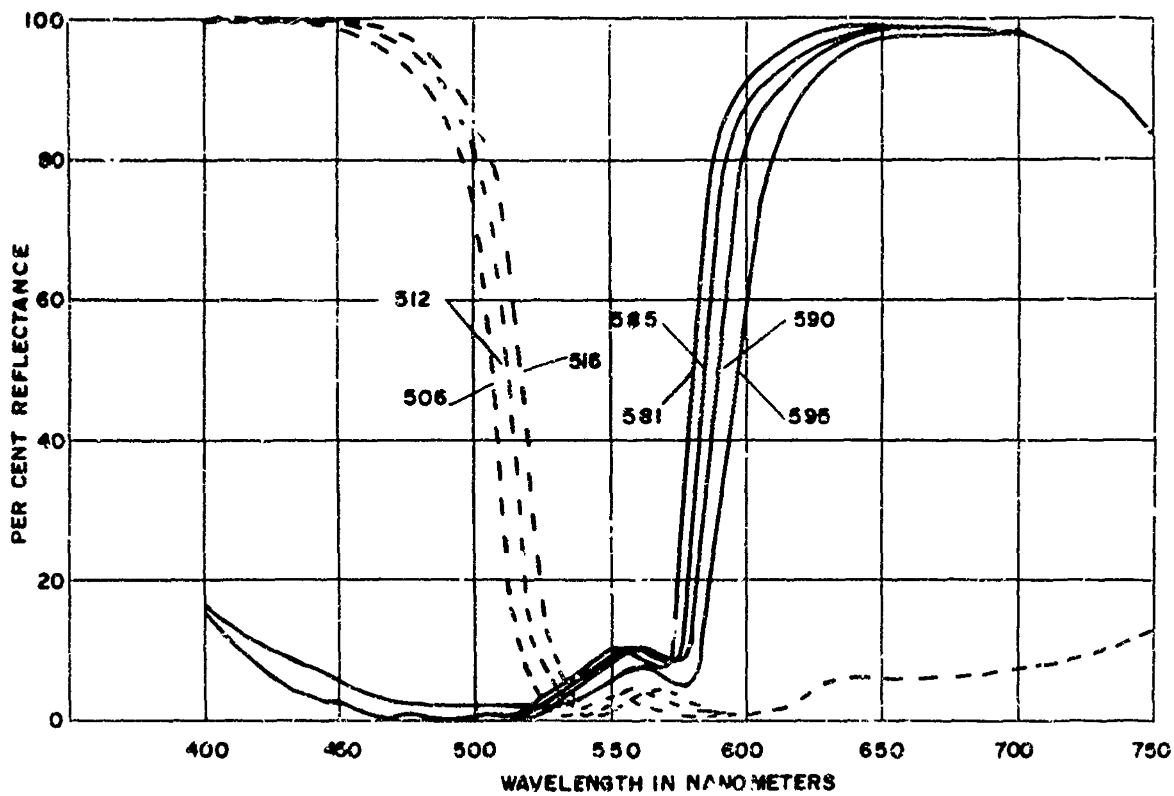

Figure 3. Spectral Reflectances and 50 Percent Cutoff Points of the Three Blue and Four Red Dichroic Filters at 60° Angle of Incidence

The blue coding color showed a regular increase in luminosity from the 506 to the 516 filters. Luminosity is indicated by the height of the point on the y-axis, the proportion of the CIE green primary which also accounts for the luminosity. All red coding colors appeared to be very highly saturated, as little distance was observed between the red points and the spectrum locus. This distance is an indicator of saturation. The green coding color was a function of the combined effects of the three blue and four red filters. Consequently, 12 discrete points were obtained with the Color-Rad. The obtained white coding color gave various readings, depending on which blue

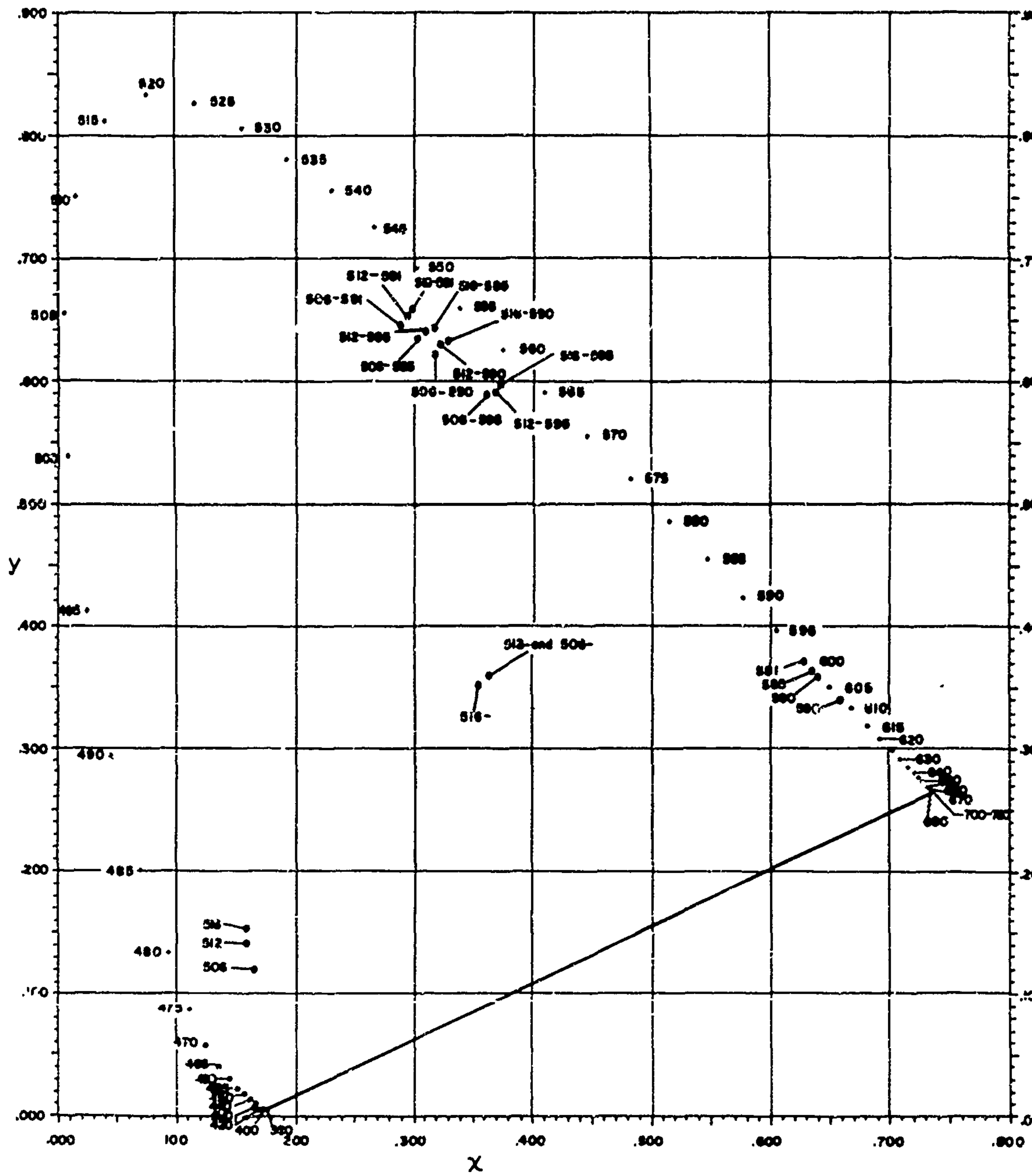

Figure 4. CIE Chromaticity Coordinates for the Three Primary and White Color Codes Produced by the Twelve Dichroic Filter Pairs

filter was used. To test whether these differences were associated with the filters or were random error, Hotelling's T^2's (Winer, 1962) were calculated for four measurements each on the white color codes produced by the three blue filters. T^2's between the 516 and 506 filters' whites and between the 516 and 512 whites were significant, possibly due to ageing effects on the older filter, the 516. The 516 white and 506-512 whites were plotted separately. The chromaticity coordinates of the remaining color codes were estimable as the intersection of two lines. The first line connected the two primaries making up the coding color being measured. The second line connected the third primary, not involved in the color mixture, the white color code point, and the first line. Yellow, magenta and cyan were thus determined as if they were complementaries of the third primary.

4. STIMULI

Four randomizations of an alphanumeric matrix were obtained on Kalvar 70 mm film. The matrices contained all alphanumerics in each of the seven colors, randomly arranged in an 18 column by 14 row format.

5. RELEVANT DISPLAY VARIABLES

To the left of the projector, 5.1 degrees offset from the 24.3 foot screen-projector axis, the subject sat 22.5 feet from the screen center. The displayed characters had an apparent height of 27 minutes of arc. Ambient light from the environment's fluorescent light system was reflected from the screen at 0.33 foot-lamberts. The open-gate brightness of the projector, including ambient on the screen, was 4.0 foot-lamberts. The limit of allowable misregistration was a conservative 33 percent (Snadowsky, Rizy and Elias, 1964).

6. SUBJECTS

Subjects were 12 male college students between the ages of 18 and 26 with visual acuity of between 20/18 and 20/29, corrected or uncorrected. Subjects had normal color vision as tested by the pseudoisochromatic plate in the Bausch & Lomb Orthorater series.

7. EXPERIMENTAL DESIGN

A $4 \times 12 \times 7$ factorial design with partially repeated measures was used. There were four orders of presentation of filter pairs, counterbalanced in a Latin square to control learning, with three subjects viewing each order. Each subject was tested under each of the following conditions: twelve blue/red filter combinations, all possible pairs of blue filters 506, 512 and 516 followed by red filters 581, 585, 590 and 595; seven coding colors in the order of white, red, green, blue, yellow, magenta and cyan.

8. PROCEDURE

All subjects were given a practice session in which they viewed eight alphanumeric randomizations twice, to become familiar with the task and display and to reduce rapid improvements in experimental performance due to learning. In the experiment, each group of three subjects viewed displays generated by three filter pairs per day, one red filter paired with each of the three blue filters. For each filter pair, the subject viewed four alphanumeric randomizations. The four scores of number of characters correct per trial were totalled for each level of filter pair/coding color to provide an aggregate score, ignoring any difference between the four alphanumeric slides used. Subjects were instructed to read as many alphanumerics of the experimenter-designated color as possible within the 12-second exposure time.

SECTION III

RESULTS

The number of characters in the designated coding color read correctly by the subject within the allowed time interval was the response chosen for analysis. This "correct identifications" score was previously determined (Rizy, 1965) to be the most adequate, in terms of sensitivity and convenience. Transformation of scores was not judged necessary, since inspection and preliminary testing indicated data met the assumptions underlying parametric analysis. The summary of the analysis appears in Table I.

Table I

Summary of Analysis of Variance for Effects of Order, Filter Pair and Coding Color

Source of Variation	d.f.	Mean Square	F-Ratio
Between Subjects	11		
Order (0)	3	65 489.28	3.591
Subjects within groups	8	18 235.73	
Within Subjects	996		
Filter Pair (P)	11	124.30	1.934*
O × P	33	584.65	9 095**
P × Subjects w. groups	88	64.28	
Coding Color (C)	6	18 871.83	18.541**
O × C	18	340.25	.334
C × Subjects w. groups	48	1 017.84	
P × C	66	45.03	3.000**
O × P × C	198	17.02	1.134
P × C × Ss w. groups	528	15.01	
		*$p < 0.05$	**$p < 0.01$

The main effect of filter pair was significant at $p = 0.05$. The magnitude of difference between the highest and lowest average scores for filter pairs was approximately 1.3 units, as shown in Figure 5. The relationship between subject performance and filter pairs, however, was not immediately obvious, although performance with the 506 blue filter tended to be lower than with the other two blue filters; and the 595 red filter tended to have greater variability than the other red filters. Specific differences between filter pairs were analyzed by the Tukey (a) test of "honestly significant differences" (Winer, 1962) which determined only one significant difference, between the 512/595 and the 506/595 pairs.

The main effect of coding color was also significant, but far beyond the 0.01 level. Subject performance, as shown in Figure 6, was highest for yellow, lowest for blue. A second Tukey (a) test was calculated for coding color and is summarized in Table II. Coding colors appeared to fall into two categories, the "high" performance codes: yellow, red, magenta and white; and the "low" codes: green, cyan and blue.

Table II

Summary of the Tukey (a) Test on Coding Color *, **

Coding Color						
Yellow	Red	White	Magenta	Cyan	Green	Blue
22.02	20.90	20.26	19.57	16.80	16.07	14.26

*Scores reported in terms of mean correct responses per 12-second trial.

**Experimental conditions connected by a line are not significantly different at $p = 0.05$.

The interaction of order with filter pairs (O × P) was significant, indicating that learning continued within the experiment, thereby justifying the counterbalanced design. Finally, the interaction of filter pairs and coding colors was significant ($p < 0.01$), indicating that the relative efficiency of filter pairs changed from coding color to color. Since the main effect of filter pair was not as yet clearly defined, testing of this interaction was postponed.

The analysis of filter pairs can logically be regarded as an analysis of interaction. Separate analyses were calculated for the main effects of the red filter with the scores for the individual blue filters combined and vice versa and appear in Tables III and IV. The ratios of some components of variation do not change from the general analysis (Table I) to the restricted analyses, i.e., F-ratios for Order, Coding Color, and Order by Color interaction, since the components of variation involved were not affected by the combining of scores.

The red filters were statistically equivalent overall, but did interact significantly with Order and with Coding Color. The R × O interaction was a function of the order of presentation, since only one red filter with each of the three blue filters was presented in a single day. For the same reason, the B × O interaction was not significant.

The blue filters were significantly different ($p < 0.01$), and a significant interaction between blue filters and coding colors was also identified. A Tukey (a) test was calculated for blue filters averaged over all other conditions. The 506 blue filter was significantly lower ($p < 0.01$) than either the 512 or 516 filters, which were statistically equivalent.

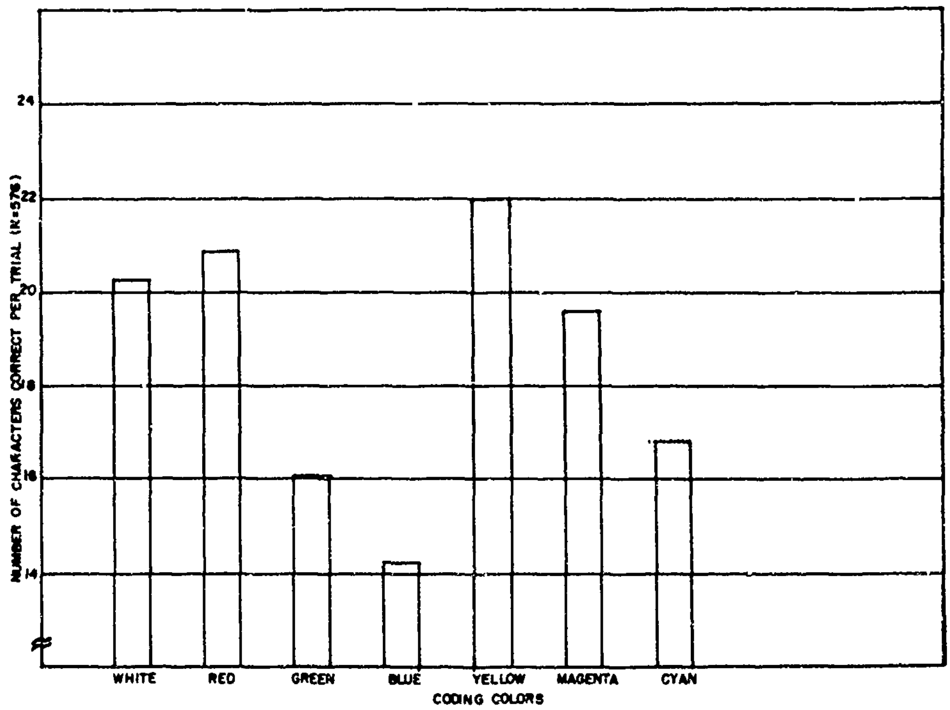

Figure 5. Average Performance on Dichroic Filter Pairs

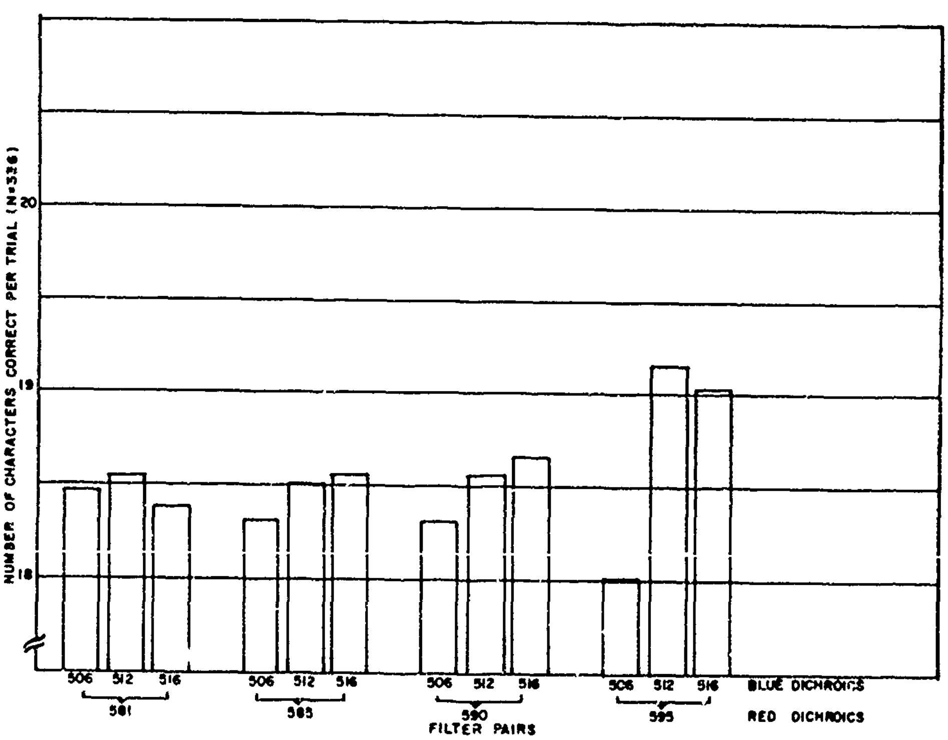

Figure 6. Average Performance on Coding Colors

Table III

Summary of Analysis of Variance for Red Filters, with Blue Filters Combined

Source of Variation	d.f.	Mean Square	F-Ratio
Between Subjects	11		
Order (O)	3	196 467.83	3.59
Subjects within groups	8	54 707.21	
Within Subjects	324		
Red Filter (R)	3	184.62	.51
O × R	9	5 362.66	14.90**
R × Subjects w. groups	24	359.86	
Coding Color (C)	6	56 615.48	18.54**
O × C	18	1 020.74	.33
C × Subjects w. groups	48	3 053.51	
R × C	18	247.57	4.44**
O × R × C	54	68.76	1.23
R × C × Ss w. groups	144	55.78	

Table IV

Summary of Analysis of Variance for Blue Filters, with Red Filters Combined

Source of Variation	d.f.	Mean Square	F-Ratio
Between Subjects	11		
Order (O)	3	261 957.11	3.59
Subjects within groups	8	72 942.94	
Within Subjects	240		
Blue Filter (B)	2	1 161.79	8.75**
O × B	6	244.32	1.84
B × Subjects w. groups	16	132.71	
Coding Color (C)	6	70 570.65	18.56**
O × C	18	1 333.21	.33
C × Subjects w. groups	48	4 071.34	
B × C	12	301.98	4.62**
O × B × C	36	67.98	1.04
B × C × Ss w. groups	96	65.35	

**$p < 0.01$

Tukey (a) tests were also calculated for coding colors for each of the red and blue filters and appear in Table V. While this was not the customary way to treat interaction effects, the main interest of the investigation was the selection of "good" dichroic filters -- for performance on the color codes in general and for particular codes if possible.

Table V

Summary of Tukey (a) Tests for Color Code Interaction with Red Filters and Blue Filters Considered Separately*, **

Color Code	Red Filters			
White	581	585	590	595
	20.61	20.51	20.18	19.74
Red	595	585	581	590
	21.57	20.80	20.67	20.55
Green	No significant differences observed			
Blue	595	590	581	585
	15.15	14.35	13.80	13.74
Yellow	No significant differences observed			
Magenta	No significant differences observed			
Cyan	595	585	590	581
	17.14	16.92	16.68	16.46
	Blue Filters			
White	No significant differences observed			
Red	512	516	506	
	21.39	21.26	20.05	
Green	No significant differences observed			
Blue	516	512	506	
	14.87	14.29	13.61	
Yellow	No significant differences observed			
Magenta	No significant differences observed			
Cyan	No significant differences observed			

*Scores reported in terms of mean correct responses per 12-second trial.

**Experimental conditions connected by a line are not significantly different at p=.05. Critical value used MS_{error} of filter/color interaction.

The restricted analyses identified one "inferior" filter, the blue 506. The Tukey tests summarized in Table V indicated that the red filter 581 was adequate for white but probably produced a poor cyan. The red 595 was poor for white but best in the red, blue and probably cyan color codes. The 516 blue filter produced the best blue coding color but in all other codes was equivalent to the 512 blue filter. Paradoxically, two blue filters were associated with better red color codes than the other, and significant differences were found among red filters for the blue color code.

SECTION IV

DISCUSSION

1. MAIN EFFECT: CODING COLOR

Performances on the seven coding colors were found to be significantly different. Yellow, red, white and magenta were statistically equivalent. Cyan, green and blue yielded equivalently low performance. This was the third time that the relative efficiency of the seven coding colors had been compared.

In an investigation of misregistration (Snadowsky, Rizy and Elias, 1964), at perfect registration the order of efficiency of coding colors was: red, yellow, blue, magenta, white, green and cyan. The ratio between open-gate and ambient brightness approximated 5800:1. Using the contrast formula, $C = (Bt - Bb)/Bb$, where C = Contrast, B = Brightness, t signifies the target and b the background, contrasts for the various colors were: white, 66; red, 16; green, 44; blue, 6; yellow, 60; magenta, 22; and cyan, 50.

In the first filter specification study (Rizy, 1965), an ambient condition of approximately 0.09 foot-lamberts was introduced. Open-gate to ambient ratio was reduced to 13.3:1. The same order of color efficiencies was maintained with the exception of blue, which became not significantly different from cyan and green. Contrasts for the primary color codes were determined but varied according to the particular filters used in the projector. Contrasts were: for red, from 1 to 3.6; for green, from 4.3 to 8.3; and for blue, from 1 to 1.5.

In the present research, the open-gate to ambient ratio was further diminished, to approximately 11.5:1. In this case, yellow was higher than red, white above magenta, and blue lowest for observer performance.

While no significant differences were identified in these shifts over the three studies, except between blue and other colors, an interesting trend seemed apparent between the relative efficiencies of coding colors and the levels of display brightness and ambient brightness used. If a certain amount of latitude exists in the operational case, the engineer can practically "customize" the efficiency of colors to their relative frequency or importance in the coding scheme of a given system. The effect of contrast on legibility is probably largely independent of the particular filters used and will be investigated later as a separate research problem.

2. MAIN EFFECT: FILTER

Statistical analyses identified only one filter related to significantly poorer-than-average performance: the blue dichroic filter with a 50 percent cutoff at 506 nanometers. This finding effectively sets a lower limit on the cutoff point for blue reflectors at about 512 nanometers. Due to unavailability of other experimental filters up to the present time, the upper limit is at least 516 nanometers.

The range of red filters of overall equivalence remained from 581 to 595 nanometers. Further research should extend this range to determine where performance begins to decrease. The selection of a particular red filter should also, however, take into account the filter/coding color interaction.

3. FILTER CODE INTERACTION

The 506 blue filter was found significantly poorer than other filters for both blue and red color codes. Whereas the relation between blue filter cutoff and efficiency of the blue color code was apparent (the higher the cutoff, the brighter the color code), exactly why the same blue filter should be associated with a poor red code was not so obvious.

One suspicion, that the blue 506 changed the CIE values for the red in some unfavorable direction, was logical but not supportable. The Color-Rad could not distinguish between the red primaries as a function of blue filter but only of red filter. An alternative explanation was that low blue luminance caused red and magenta to be confused. However, the magenta color code did not significantly interact with filters, which would indicate that any hypothetical confusion would also have to be unidirectional, i.e., that red was confused with magenta but not vice versa.

The same type of influence was noted regarding the red 595 filter, namely that it produced more efficient red and blue color codes. Since the red filter occurred after the blue filter in the filter sequence used in this study, it was practically impossible for the red filter to alter the physical dimensions of the blue color code. This was apparently, as in the case above, an instance where slight shifts of part of the color repertory influenced the observer's perception of other parts of the same system, a kind of color contrast effect.

4. APPLICABILITY OF CRITERIA

Coding colors obtained by two representative filter pairs, 516/581 and 516/595, were plotted on Kelly's (1943) data, in Figure 7. Both green codes did not fall within the typical green area. To accomplish this, the red filter's cutoff would probably have to be moved into the orange. The present selection of green color codes has been consistently poor, and available filters have had no significant effect in changing performance in the green category.

Both red codes were not in the true red region, although this did not seem to affect performance. The red code closest to the true red region was significantly better than the other. A true red was obtained by a filter cutting off at 619 nanometers in the previous study on color specification. Subjects did more poorly on that code, however, probably because of the corresponding low luminosity.

The blue obtained by the 516 filter fell within the blue region of Kelly's figure. Cutoffs of less than 516 (Figure 4) entered the purplish blue area, with associated decrease in luminosity and subject performance. The most efficient color code, yellow, fell within Kelly's specified yellow region.

No significant differences were found between the various magenta codes, including the two samples shown, although by Kelly's standard and by visual inspection they were apparently different. Cyan produced by the 581 red filter, while having greater saturation than the 516/595 cyan, gave poorer subject performance at the 0.05 level of probability. Kelly's data do not seem to account for this particular finding. In summary, Kelly seems to have set a conservative criterion. The dichroic filter-xenon source situation did not completely meet this criterion and yet still produced what appeared to be, in the experimental case, adequately identifiable colors. Greater freedom in choosing the chromaticities of coding colors, such as using trimming filters in the additive color projector or employing the highly saturated primaries found in electroluminescent or laser display techniques, will allow, in all probability, greater satisfaction of the Kelly standard and much better coding colors.

The coding colors obtained by the same pairs of filters were also plotted on Judd's summary of findings on color confusion in Figure 8. Codes produced by each of the filter pairs were separated from each other by at least one interpolated elliptical diameter, approximating 200 times the minimum perceptible difference, except in three doubtful cases: cyan-white, cyan-green, and white-yellow. Subjects apparently confused these pairs of colors in the previous study (Rizy, 1965). In the present study, color confusion was so little evidenced that it could not be effectively dealt with as a measure of performance. Application of Judd's findings may appear to be dangerous when interpolation is employed. On the face of things, however, the coding colors plotted here appeared to meet the minimum criterion for excluding confusability. Again, more highly saturated primaries and particularly a less yellowish green would tend to increase the distance between colors on the confusability figure and result in more discriminable coding colors.

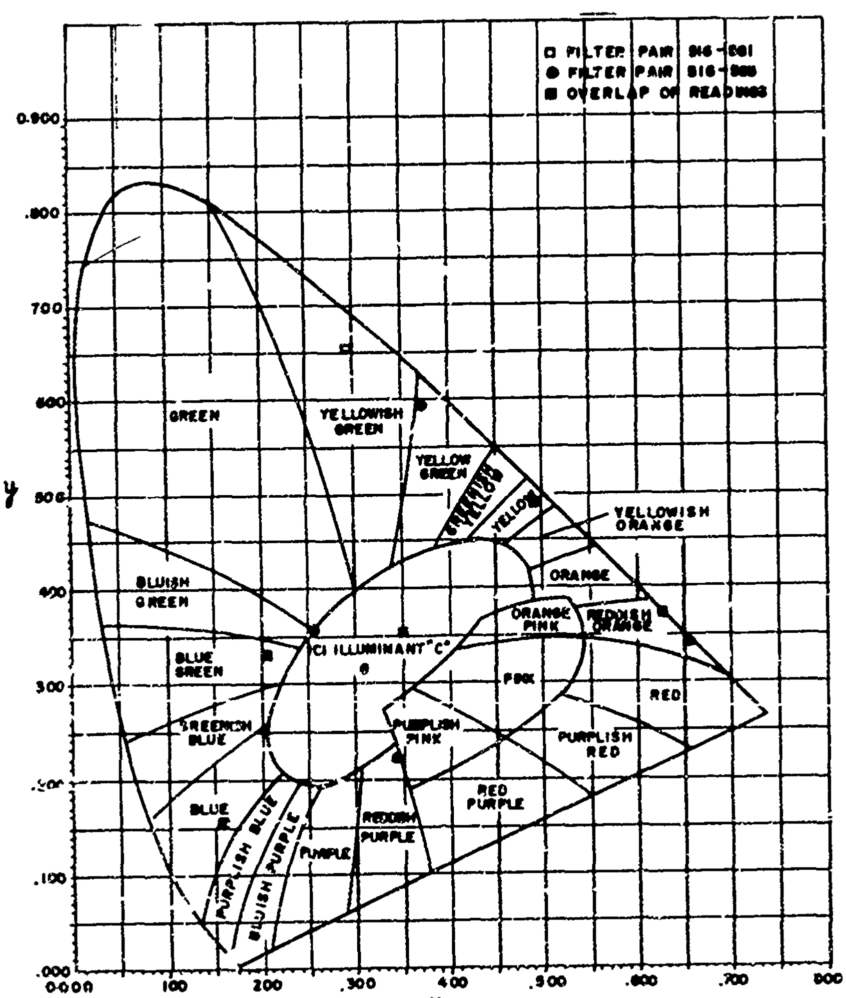

Figure 7. Plots of Coding Colors Produced by Two Representative Filter Pairs on CIE Areas Designated Color Names by Kelly (1943)

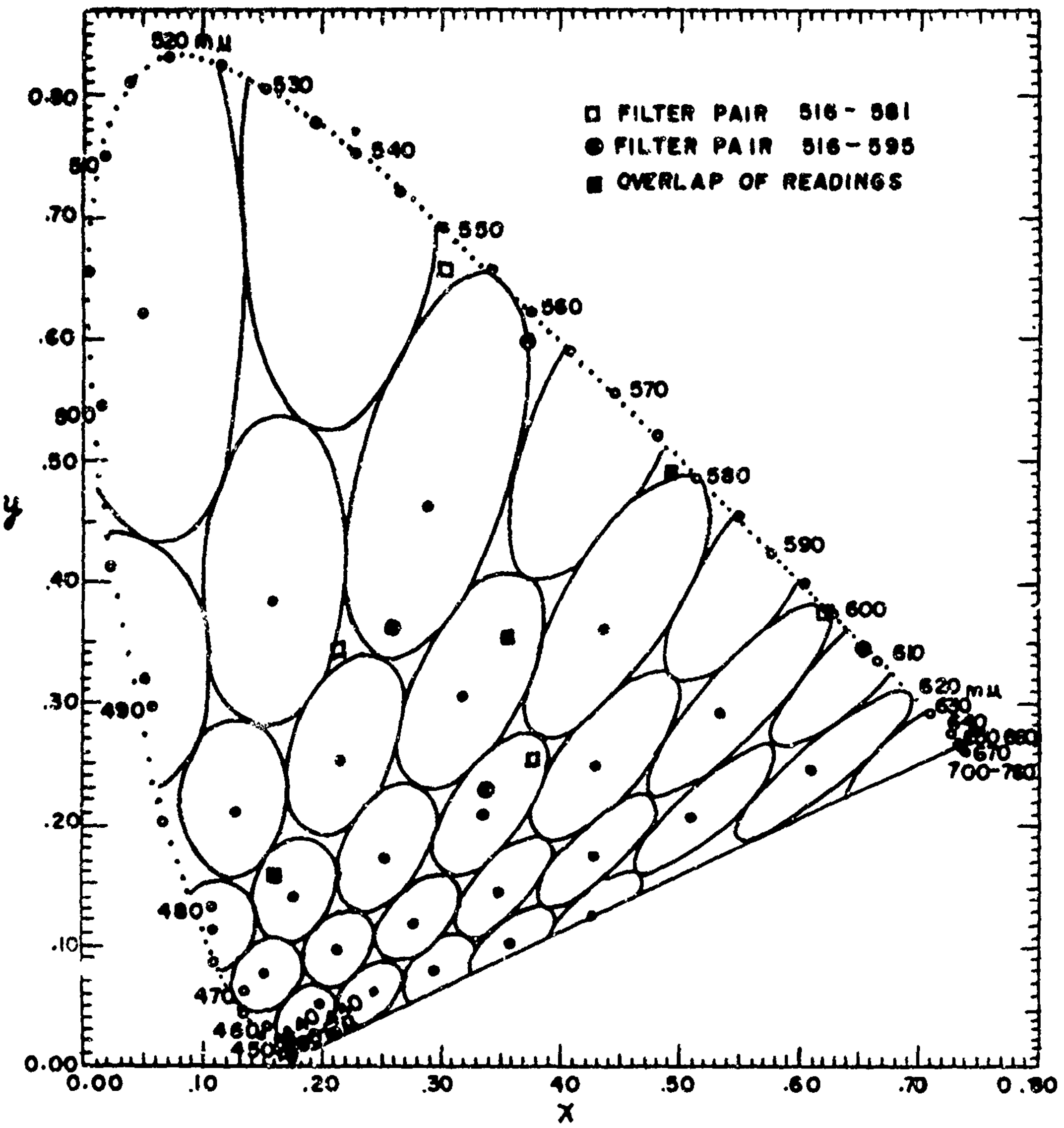

Figure 8. Plots of Coding Colors Produced by Two Representative Filter Pairs on CIE Ellipses Designated Confusion Contours by Judd (1950)

SECTION V

CONCLUSIONS

Observer performance on reading alphanumerics coded in each of seven colors indicated that the optimum blue-red filter order should employ a blue dichroic filter cutting off between 512 and 516 nanometers and possibly higher than 516. Red filters should cut off between 581 and 595 nanometers for the production of satisfactory color codes. The significant filter by color interaction indicated that certain filters produced better or worse coding colors than the average of filters. These preferences for filters can be expressed as follows:

Symbol Color	Preferred Filters	Poor Filters
White	581-585 Red	595 Red
Red	595 Red	506 Blue
Green	No differences among filters	
Blue	595 Red, 516 Blue	506-512 Blue
Yellow	No differences among filters	
Magenta	No differences among filters	
Cyan	595 Red	581 Red

Proper use of the filter specification and manipulation of the brightness of the display and ambient illumination should allow the system designer to make the most frequently used or most important coding colors also the most legible and identifiable. The applicability of two types of criteria based on the CIE diagram seemed generally valid in the color coding situation. Use of these standards should assist greatly in the prediction of the relative efficiency of future color codes.

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APPENDIX

THE ORDER OF DICHROIC FILTERS IN AN OPTICAL ASSEMBLY

The full range of seven colors may be obtained using various orders of dichroic filters. A blue dichroic may be inserted into the light path, followed by a red filter. This is the most common approach, adopted by the manufacturer of the projector used here and by the Orthicon system (Moodey, Neuhauser, Richards and Headrick, 1957) used in commercial color television cameras. The apparent rationale behind this order is that blue, the least luminous of colors, loses none of its energy through internal reflection or through other filters placed earlier in the light path. Red filters, for instance, tend also to reflect some energies in the blue region of the spectrum.

Other conceivable orders include red-blue, red-yellow (the yellow component appearing green with red previously removed), and blue-cyan (cyan appearing green with blue first taken out). No advantages are foreseen with orders different from blue-red. This area is being reserved for future investigation.

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13. ABSTRACT

Twelve pairs of dichroic filters were used in a xenon-source additive color projector to determine their effects upon observer use of the seven color codes customarily employed in Command-and-Control visual displays. The particular filters used were selected on the basis of previously published research. The resultant primary color codes and white were described in CIE terms for more ready comparison with color discrimination literature.

Results indicated that the blue filter should reflect energies well into the green region of the spectrum for adequate seven-color production. No overall differences were found among the red dichroics, although red filters interacted significantly with coding colors. It was concluded that the relative efficiencies of the seven color codes may be tailored to anticipated or present operational need by the utilization of narrow filter tolerance. Broader tolerances around 516 nanometers for the blue filter cutoff and 585-590 nanometers for the red cutoff should result in an adequate set of seven coding colors. A comparison of several studies completed over the past two years seemed to suggest that overall display brightness may have almost as significant effect on observer performance as the selection of filters.

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